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13. ABSTRACT (Maximum 200 words)

Our research concerned the manners by which the "monaural" and "binaural" auditory systems process information in complex sounds. Substantial progress was made consistent with the objectives outlined in the original proposal in three areas: 1) New electronic equipment, including a NeXT computer was purchased, installed and interfaced with the existing laboratory. Software was developed for generating the necessary complex digital stimuli and for running behavioral experiments utilizing those stimuli. 2) "Monaural" experiments showed that the CMR is not obtained "successively" and is reduced or non-existent when the flanking bands are pulsed rather than presented continuously. "Binaural" investigations revealed that the detectability of a tonal target in a masking-level difference paradigm could be degraded by the presence of a spectrally remote "interfering" tone. 3) In collaboration with Dr. Richard Stern, theoretical efforts included the explication and evaluation of a weighted-image model of binaural hearing, attempts to extend the Stern-Colburn position-variable model to account for many crucial lateralization and localization data gathered over the past 50 years and the continuation of efforts to incorporate into a general model notions that lateralization and localization of spectrally-rich stimuli depends upon the patterns of neural activity within a plane defined by frequency and interaural delay.

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Monaural and binaural processing of Complex Waveforms

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Keywords: centrality, CMR, cross-correlation, generation of complex digital stimuli, interference, masking, MLD, off-frequency cuing, straightness

In order to facilitate use of information provided in this document, we have combined categories included in amendment No. 2 to "Administration of U.S Air Force Grants and cooperative Agreements for Basic Research" Brochure and will include essentially two reports: 1) a "short form" that contains extremely concise statements that are elaborated upon in 2) a"long form" that provides more detailed information regarding each facet of our progress.

SHORT-FORM PROGRESS REPORT

92-05465

I) Progress concerning hardware and software

a) Purchase and set-up of new equipment

1) All electronic equipment (switches, programmable attenuators, filters, etc) requested in the original proposal was purchased and interfaced.
2) A NeXT computer system was purchased and enables the comparison of predictions of the comprehensive model of binaural hearing developed with Dr. stern and his colleagues with our behavioral data concerning the lateralization of intracranial images produced by combinations of interaural temporal and intensive disparities.

b) Development of specialized software

1) Specialized software was developed for generating the complex digital stimuli necessary for the experiments proposed. This allowed for the generation of stimuli with specific combinations of desired envelope and fine- structure information.
2) Specialized routines were written to interface this new software with the ILS signal-processing package.
3) New software was developed to run the experiments utilizing the digitally-constructed, complex signals. Specifically, this was required for the experiments in which the "signal" consisted of information only in the envelope that was out-of-phase across two otherwise identical narrow bands of noise that differed in their center frequencies. This development also involved new techniques to integrate analog and digital stimuli so that an essentially continuous analog background could be turned off and replaced by its digital counterpart.
4) New signal-processing software was developed to measure changes in the interaural and/or intersignal correlation that results when a particular target is added to a particular background. The major benefit is that these measurements can now be performed on digitally-generated stimuli rather than via the sampling of analog electrical waveforms.

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5) Signal-processing programs were written to determine the spectral consequences of manipulating features of only the envelope of narrow bands of noise. These were necessary to increase our understanding of the effects produced when envelopes and fine-structures are mis-matched and no longer co-vary as they do in a "naturally-occurring", Gaussian, narrow band of noise. Such manipulations of the envelope are fundamental to the construction of "signals" in a large portion of the proposed experiments concerning the CMR.

II) Progress concerning our program of research

a) Monaural behavioral experiments

1) It does not appear that a CMR can be obtained successively(i.e., when the "off-frequency" or flanking information occurs before and after, but not simultaneously, with the signal and nominal masker).
2) It also appears that CMR's are much reduced or non- existent when the flanking bands are pulsed rather than presented continuously.
3) Experiments were begun to determine by how long the flanking bands must precede the signal in order 1) to obtain a sizeable CMR and 2) to obtain a CMR essentially equal to that obtained with continuous masking and flanking bands. It appears that turning on the masking and flanking bands as long as 320 ms before the beginning of the signal does not produce a CMR as large as that obtained with continuous bands of noise.
4) Experiments were begun that were designed to determine the magnitude of the CMR when the "signal" consisted of information in the envelope that was out-of-phase across two otherwise identical narrow bands of noise that differed in their center-frequencies.

b) Binaural behavioral experiments

1) It was discovered that the detectability of a tonal target presented in a masking-level difference paradigm (NoSo vs. NoSπ) can be greatly degraded if a second, spectrally remote, "interfering" tone is presented in both intervals of a 2IFC task. Our initial data indicated that this "interference" is greatly dependent upon the interaural configuration of the interferer, its level, and, especially, its frequency relation to the frequency of the target. Our findings were published in a publication entitled "Spectral interference in a binaural detection task" in the March, 1991 issue of the Journal of the Acoustical Society of America.
2) The magnitude of this type of interference was assessed as a function of the temporal relations among targets, maskers, and interferers and, importantly, the bandwidth of the maskers. It was discovered that :

    i) Pulsing the interferer simultaneously with the target produces the greatest interference
    ii) Presenting the interferer continuously produces the least interference
    iii) Providing more and more of a leading interfering "fringe" often reduces the interference. However, even beginning the interferer as much as 320 ms <u>before</u> the onset of the target typically results in more interference than that found with a continuous interferer.
    iv) Substantially more interference (but not masking) is observed when the target is masked by a continuous <u>narrow-band</u> noise than when the target is masked by a continuous <u>broad-band</u> noise

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III) Progress concerning theory

1) Explication and evaluation of a weighted-image model of binaural hearing which is an extension of the Stern-Colburn position-variable model was completed. This resulted in a paper entitled "Lateralization of bands of noise: Effects of andwidth and differences of interaural time and phase", which appeared in the October, 1989 issue of the Journal of the Acoustical Society of America.
2) Ongoing discussions and attempts to understand, in detail, the binaural system's use of interaural temporal and intensitive disparities resulted in the presentation of a poster at the Fall, 1988 meeting of the Acoustical Society.
3) Concentrated discussions surrounding the Fall, 1988 presentation led to the realization that proper modifications of the Stern-Colburn position-variable model could account for many crucial data gathered in lateralization and localization experiments over the past 50 years. In essence, it appears that a generalized cross-correlation model appears to be utilizable for explaining both the intracranial and external locus of sounds.
4) Notions that lateralization (and presumably localization) of spectrally-rich stimuli depends upon the patterns of neural activity within a plane defined by frequency and interaural delay were further incorporated into a general model of binaural hearing.
5) Extensions of notions described in 4) to data collected at high frequencies was begun.
6) Attempts were begun to incorporate the processing of interaural intensitive differences into this model so that quantitative predictions can be made for stimuli that are realistically complex in terms of their interaural parameters.

LONG-FORM PROGRESS REPORT

I) Progress concerning hardware and software

a) Purchase and set-up of new equipment

We purchased all of the electronic equipment (switches, programmable attenuators, filters, etc) requested in the original proposal including a 386-based computer system which, in all respects, is superior to what was available at the budgeted price at the time we wrote the proposal.

We purchased a NeXT cube computer system that essentially mimics, functionally, the system used for development and implementation of a comprehensive model of binaural information processing by Dr. Richard Stern and his students at Carnegie-Mellon University. Dr. Stern served as a consultant for this program of research in particular and as a collaborator in diverse investigations of binaural hearing.

Upon the arrival of our NeXT computer, Dr. Stern brought the necessary software so that both laboratories (ours and his) can now obtain quatitative predictions from the model using the efficient graphical interface developed in Dr. Stern's laboratory. This enabled us to compare predictions of the model to our behavioral data concerning the lateralization of intracranial images produced by combinations of interaural temporal and intensitive disparities.

b) Development of specialized software

The 386-based computer and new ancillary equipment required a good deal of specialized software to be written above and beyond that which already existed.

Nevertheless, all of the equipment and the software were in-place and functional early in the granting period.

Generation of the complex digital stimuli required for many of the experiments involved the development of new software that incorporated the algorithms necessary to manipulate separately and independently, the constituent temporal components of the waveforms. Specifically, this software allowed us to create complex signals with proper envelopes, phase modulation and fine-structure. In addition, a set of specialized routines were written to merge the customized signal-processing software with the ILS signal-processing package. This was necessary in order to capitalize on the capabilities of ILS while also being able to perform all the required manipulations demanded by the diverse signals to be employed in the various projects.

A separate, and equally complex, undertaking involved the creation of programs to run the experiments utilizing the host of digitally-constructed, complex signals possessing the desired temporal features. This turned out to be no mean feat. These experiments required the use of digitally-generated stimuli where the "signal" consisted of information only in the envelope that was out-of-phase across two otherwise identical narrow bands of noise that differed in their center frequencies. After conducting experiments with such signals, it became clear that it was necessary to conduct similar experiments in which the bands of noise were continuous, or at least very long as compared to the duration of the signal to be detected. Rather than deal with huge arrays of digital signals, we chose to present our digital stimuli against a background of stimuli generated with analog equipment. To accomplish our tasks, it was necessary to integrate analog and digital stimuli so that the essentially continuous analog background would be turned off and replaced by its digital counterpart. Of course, this had to be done with precise timing in a manner that would be transparent to the listeners. We were gratified to find that these efforts resulted in stimuli that were "seamless" and, therefore, suitable for our purposes.

Yet another major programming undertaking involved the development of signal-processing software to measure changes in the interaural and/or intersignal correlation that results when a particular target is added to a particular background. This constituted a major upgrading and departure from a somewhat similar scheme employed by one of us, LB, at the University of Florida. The major benefit is that these measurements can now be performed on digitally-generated stimuli rather than via the sampling of analog electrical waveforms. The "analog" method required manual adjustment in order to vary relevant parameters of the stimuli. The new method allows us to make these adjustments digitally through software. The result is that many measurements can be made much more quickly and can even be done after working-hours as the presence of a human is not required. Even the 386-based computer requires upwards of six hours to perform only one set of relevant measurements.

A very important set of signal-processing programs were written to determine the spectral consequences of manipulating features of only the envelope of narrow bands of noise. These were necessary to increase our understanding of the effects produced when envelopes and "fine-structures" are mis-matched in the sense that the phase-modulation and amplitude-modulation no longer co-vary as they do in a "naturally-occurring", Gaussian, narrow band of noise. Such manipulations of the envelope are fundamental to the construction of "signals" in a large portion of the proposed experiments concerning the CMR. Even though we have had extensive prior experience with some stimuli containing such mis-matches (Amenta et. al., 1987), we, and many of our colleagues continue to be surprised. That is, quite often our intuitions, that are based on much hands-on experience, are incorrect. We feel strongly that our time was well invested and we will continue to share our new insights with our colleagues both formally and informally.

II) Progress concerning our program of research

a) Monaural behavioral experiments

Three sets of data were collected regarding the comodulation masking-release. One set concerned whether a CMR can be obtained when the coherent envelope information is presented successively rather than simultaneously. The experimental paradigm consisted of a four-interval task in which the target to be detected was presented with equal probability in either the second or third interval. The first and fourth intervals served as "cues" for the noise-alone conditions. We compared the detectability of the targets when all four intervals contained identical envelope-information (within each trial) to detectability when each of the four intervals contained randomly-chosen, independent, uncorrelated envelopes. Our initial efforts indicated that there was no discernable difference in the detectability of the target between the two conditions.

This outcome appeared to rule out signal-detection notions regarding the reduction of "envelope-uncertainty" as the basis of the CMR. Before we were willing to accept this wide-sweeping negative interpretation, we felt it necessary to gather many additional data using frozen "natural" Gaussian narrow-band noises rather than noises whose envelopes and fine-structures were mis-matched. The newer data, gathered in 24 separate conditions, revealed that listeners were, indeed, more sensitive when a particular trial contained homogeneous envelope information across all four intervals. However, as indicated by our initial efforts, this increased sensitivity did not result from off-frequency "cuing" information that is the hallmark of the CMR phenomenon. When the "cuing" intervals were eliminated and only the on-frequency envelope of the masker was the same for the two remaining intervals, performance was not degraded. The data in their totality indicate that, although listeners can benefit from "on- frequency" envelope information, there appears to be no substantial additional benefit obtained when such information is provided by spectral regions flanking that containing the signal.

The lack of a CMR in the successive paradigm could, also, mean that whatever mechanisms mediate the CMR are ineffective when the flanking bands are pulsed rather than presented continuously, as is usually the case. Consequently, we also measured the CMR when the flanking and masking bands were simultaneously present, but were turned on and off together for short durations. That is, both target bands and flanking bands were pulsed. Once more, the CMR essentially vanished. We were gratified to read in a recent paper of Joe Hall's that he also observed a similar outcome and that Wright and McFadden are preparing a paper concerning similar findings.

We are now conducting experiments to determine by how long the flanking bands must precede the signal in order 1) to obtain a sizeable CMR and 2) to obtain a CMR essentially equal to that obtained with continuous masking and flanking bands. The data obtained thus far indicate that the answers to these two questions will be somewhat complicated. It appears that turning on the masking and flanking bands as long as 320 ms before the beginning of the signal does not produce a CMR as large as that obtained with continuous bands of noise. In a sense this outcome indicates that whatever mechanism underlies the CMR is quite "sluggish".

The final set of monaural experiments to be reported concerned measurements of the magnitude of the CMR when the "signal" consisted of information in the envelope that was out-of-phase across two otherwise identical narrow bands of noise that differed in their center-frequencies. These data were obtained in order to provide a strong test of the validity of the extension of Durlach's equalization-cancellation model of binaural processing to the (monaural) CMR. Initially, the experiments were run with a four-interval, pulsed-stimulus paradigm. Once again, essentially no CMR was observed. We are now collecting data utilizing longer and longer flanking bands as described above. These are the experiments

referred to much earlier in this report for which the new software, designed to wed the analog and digital stimuli, was written.

b) Binaural behavioral experiments

Another set of binaural experiments allowed us to continue to explore a new phenomenon that is of great interest. Briefly, we have discovered that detectability of a tonal target (say, an 800-Hz tone) presented in a masking-level difference paradigm (NoSo vs. NoSπ) can be greatly degraded if a second, spectrally remote, "interfering" tone is presented in both intervals of a 2IFC task. Our initial data indicated that this "interference" is greatly dependent upon the interaural configuration of the interferer, its level, and, especially, its frequency relation to the frequency of the target.

Subsequent experiments explored whether this apparently binaural interference phenomenon is related to, or produced by, the well-known, but not necessarily well-understood, phenomenon of "non-additivity" of masking. It appears that this is not the case. Our findings were discussed in detail in a publication entitled "Spectral interference in a binaural detection task in the March, 1991 issue of the Journal of the Acoustical Society of America.

In addition, we have begun to explore how the temporal relations among targets, maskers, and interferers and, importantly, how the bandwidth of the maskers affect the magnitude of the interference observed . So far, we have discovered that simply pulsing the interferer simultaneously with the target produces the greatest interference, while presenting the interferer continuously produces the least interference. Providing more and more of a leading interfering "fringe" often reduces the interference. However, even beginning the interferer as much as 320 ms before the onset of the target typically results in more interference than that found with a continuous interferer. Finally, substantially more interference is observed when the target is masked by a continuous narrow-band noise than when the target is masked by a continuous broad-band noise. These findings were discussed in a presentation at the November, 1991 meeting of the Acoustical Society of America.

We believe that this discovery is interesting and important because: 1) it reveals for the first time that binaural processing that is necessary for the occurrence of a masking-level difference can be degraded by spectrally remote information; 2) the degradation that occurs is dependent upon the relative interaural characteristics of the target and of the interferer and does not occur simply because of the presence of simultaneous inputs.

III) Progress concerning theory

Our theoretical efforts included the explication and evaluation of a weighted-image model of binaural hearing which is an extension of the Stern-Colburn position-variable model. Dr. Stern began his role as a formal consultant to our project and has visited the laboratory three times. That collaboration has already resulted in a paper entitled "Lateralization of bands of noise: Effects of bandwidth and differences of interaural time and phase", which appeared in the October, 1989 issue of the Journal of the Acoustical Society of America.

In addition, our ongoing discussions and attempts to understand, in detail, the binaural system's use of interaural temporal and intensitive disparities resulted in the presentation of a poster at the Fall, 1988 meeting of the Acoustical Society. Serendipitously, those concentrated discussions led us to the realization that proper modifications of the Stern-Colburn position-variable model could account for many crucial data gathered in lateralization and localization experiments over the past 50 years. Many seemingly contradictory results concerning the efficacy of binaural cues across frequency in experiments utilizing earphones (lateralization) or sound-fields (localization) could be explained by simply extending the aforementioned model across frequency while explicitly incorporating the

proper values of interaural disparities (even when one of these differences is zero). In essence, a generalized cross-correlation model appears to be utilizable for explaining both the intracranial and external locus of sounds if, and only if, both types of cues are addressed properly across frequency.

In addition, we are working to incorporate into a general model notions that lateralization (and presumably localization) of spectrally-rich stimuli depends upon the patterns of neural activity within a plane defined by frequency and interaural delay. To date, these notions have, principally, been applied successfully to data collected in binaural experiments whose signals were restricted to 1500 Hz and below. We have begun to extend them to high frequencies. Furthermore, we have begun to incorporate the processing of interaural intensitive differences into this model so that quantitative predictions can be made for stimuli that are realistically complex in terms of their interaural parameters. It is hoped that this endeavor will lead to a more complete, general, model of binaural hearing.

It is important to note that the bandwidth of our stimuli is a crucial parameter. We have demonstrated that bandwidth affects greatly the interaction between these two types of interaural cues in that the intracranial locus of a binaural stimulus cannot be predicted by any scheme that employs a "trading-ratio". Our principle thrust is to determine how interaural intensitive differences can be usefully incorporated into our overall pattern-processing approach that includes higher-order constructs such as the centrality and straightness of the derived neural cross-correlation patterns produced by the stimuli.

IV) Summary of publications

Our principal findings to date can be found in the several articles that we have published and they will be stated only generally here to facilitate communication about our progress.

Trahiotis and Stern, 1989

This article reports results from the behavioral studies that measured extent of laterality as a function of the center frequency, bandwidth, interaural time-delay and/or phase-shift of narrow bands of noise. These data clearly indicate how well the concepts of straightness and centrality can account for the perceived lateral position of acoustic stimuli. The data extend greatly observations reported earlier by Jeffress (1972), indicate the strong role played by the bandwidth of stimuli per se in laterality and required an extension and severe modification of existing models that, without such modification, simply could not address the data. Parsimony has been preserved because the successful cross-correlation-based models that existed (e.g., Stern and Colburn, 1978; Blauert and Cobben, 1978) were preserved as the "front end" to the pattern processor.

Trahiotis et. al., 1990

This article documents the increasing use of adaptive procedures in binaural experiments, discusses factors that determine their appropriateness and presents data that attest to their usefulness in binaural experiments. Data concerning the detectability of a 500-Hz tone presented against a background of broadband noise were obtained using both the N0S0 and N0Sπ stimulus configurations. Ten listeners were each tested for 25 sessions for each condition and thresholds were defined in the usual manner by those who use Levitt's (1971) tracking procedures. The data are extremely reliable, show absolutely no learning effects and indicate absolute sensitivities for both stimulus configurations that are identical to those found in a raft of experiments utilizing fixed psychophysical procedures. This research was in addition to that outlined in the previous proposal, is germane to our work, and reflects our continuing concerns about methodology and its use and impact upon investigations of binaural processing.

Bernstein, 1991a

This manuscript reports a new phenomenon that is of great interest. Briefly, we have found that detectability of a tonal target (say, an 800-Hz tone) presented in a masking-level difference paradigm (N0S0 vs. N0Sπ) can be greatly degraded if a second, "interfering" tone is presented in both intervals of a 2IFC task. We call this interference, and not masking, because proximity of the added tone is not sufficient to degrade performance. Interestingly, the greatest interference appears to occur when the added tone is an octave below the target. These data are the first to show that binaural processing under masking-level difference conditions can be degraded by spectrally-remote information. The interference depends upon the relative interaural characteristics of the target and of the interferer, and does not appear to reflect "non-additivity" of masking. Overall, the results strongly suggest that central, as opposed to peripheral, processes mediate the interference and, further, point to a commonality between these tasks and those that require the detection of interaural temporal disparities across spectral regions as found recently by Buell and Hafter (1988) at the University of California.

Bernstein, 1991b

This article reports a set of empirical measurements demonstrating that, when two independent, narrow-band, Gaussian noises are "mixed" or combined according to the method specified by Licklider and Dzendolet (1948) [Science, 107, 121-124], the correlation coefficient between the envelopes of the two resulting narrow-band noises is approximately equal to the square of the correlation between the waveforms. This relation also holds for waveform correlations produced by de-correlating two perfectly correlated noises by the addition of a sinusoid (at the center frequency of the noise) that is phase-reversed (N0Sπ). The relation holds *only if the signal-to-noise ratio* is small. A method is detailed whereby any desired envelope correlation may be achieved with reasonable accuracy between two noises of the same or different center-frequency. This method may prove particularly useful to a number of investigators studying listeners' sensitivities to dissimilarities in the envelope fluctuation of bands of noise occupying discrete spectral loci, a topic currently of interest. (e.g., Richards, 1987; Hall and Grose, 1990; Wright and McFadden, 1990).

Colburn and Trahiotis, 1991

This chapter is an expanded, written version of an oral presentation given at a NATO conference concerning the effects of noise on hearing. Several issues concerning the measurement and specification of the deleterious effects of noise on binaural information-processing were discussed historically but with an emphasis on modern studies. The chapter also includes a discussion of the types of complex programs of research that we feel are required to depict accurately the various effects due to noise and other types of trauma. Also included are suggestions for theoretical frameworks that will allow a better appreciation of the underlying factors that mediate common modes of processing across a variety of stimulus contexts.

V) Listing of publications and couplings

Trahiotis, C. and Stern, R. M. (1989). "Lateralization of bands of noise: Effects of bandwidth and differences of interaural time and phase," J. Acoust. Soc Am. 86, 1285-1293.

Trahiotis, C., Bernstein, L. R., Buell, T. N. and Spektor, Z. (1990). "On the use of adaptive procedures in binaural experiments," J. Acoust. Soc Am. 87, 1359-1361.

Bernstein, L. R. (1991a). "Spectral interference in a binaural detection task," J. Acoust. Soc Am., accepted, in press for March, 1991.

Bernstein, L. R. (1991b). "Measurement and specification of the envelope correlation between two narrow bands of noise," Hear. Res., in press for March, 1991.

Colburn, H. S. and Trahiotis, C. (1991). "Effects of noise on binaural hearing," in Effects of noise on the auditory system, A. Dancer, D. Henderson, R. Salvi, R. Hamernik (Eds.) (Decker, Philadelphia).

The following presentations were made at meetings of the Acoustical Society of America and the Association for Research in Otolaryngology:

Bernstein, L. R. and Trahiotis, C. (1988). "Detection and lateralization based on interaural temporal disparities: Time or phase?" J. Acoust. Soc Am. 84, S80.

Bernstein, L. R. (1989). "Spectral interference and the masking-level difference," J. Acoust. Soc Am. 86, S24.

Buell, T. N. and Trahiotis, C. (1989). "How onset, offset, and ongoing interaural delays affect lateralization," J. Acoust. Soc Am. 86, S24.

Bernstein, L. R. (1990). "Measurement and specification of the envelope correlation between two narrow bands of noise," J. Acoust. Soc Am., 88, S145.

Bernstein, L. R. and Trahiotis, C. (1991). "Sensitivity to the interaural correlation of the envelopes of high-frequency bands of noise," Midwinter meeting, ARO.

Buell, T. N. and Trahiotis, C. (1991). "Interaural temporal discrimination utilizing pairs of high-frequency, amplitude-modulated stimuli: Conditions of summation and interference," Midwinter meeting, ARO.

Bernstein, L. R. and Trahiotis, C. (1991). "Spectral interference in a binaural detection task: Effects of temporal fringe and masking bandwidth," J. Acoust. Soc Am., 90, 2266.